Title: NOX REMOVAL IN JET-ENGINE TEST CELL EXHAUST: PROPOSED NON-THERMAL PLASMA SYSTEMS AND ECONOMIC CONSIDERATIONS

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the US Strategic Environmental Research & Development Program (SERDP)

for support for this work.

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Outline of talk

- Motivation for and applications of research
- Background of atmospheric-pressure, non-thermal plasma processing for environmental applications (air-pollution control)
  - Basics of radical formation & decomposition chemistry
  - Figures-of-merit & costs for decomposition of example pollutants
- Removal of NO$_x$ and VOCs from jet-engine test facilities
  - Plans for field demonstration of pilot unit
  - Candidate NTP systems
  - Economic considerations (candidate systems compared to conventional)
- Future trends
- Summary
Technology-development motivators are regulatory, economic, and social

**Regulatory**
- New and/or more stringent regulations
  - Clean Air Act Amendment of 1990, Clean Water Act
  - Attendant MACT standards
- Enforcement of regulations

**Economic**
- Impact of regulations
- Costs associated with conventional methods

**Social**
- Environmental consciousness
- Health risks

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The CAAA 1990 contains three titles closely related to NTPs

- Title III (Air Toxics)
  - Directly concerned with emission of hazardous air pollutants (HAPs)
  - Established standards for 189 listed chemicals

- Title IV (Acid Rain)
  - Reduction of SOx/NOx emissions

- Title VI (Stratospheric Ozone)
  - Phase out of VOCs

- MACT (Max Achievable Control Technology) Standards
  - Calls for state-of-art pollution control equipment
  - Require changes in equipment, processes, treatment

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Regulations for engine test facilities are changing under CAAA 1990 10-yr provisions

- Previously, engine test facilities were considered mobile sources because engines were moved in and out of the facilities for testing operations. However, the test facility itself was usually a permanent structure.

- The upcoming new standards will consider the test facilities as stationary sources, which are regulated differently (more stringently) than mobile sources.

- The test-facility emissions (primarily NO$_x$ and volatile organic compounds - VOCs) have dilute concentrations (e.g., < 50 ppm) and very high ($\sim 10^6$ - $10^7$ Nm$^3$/h) exhaust-gas flows.

- Consequently, new emissions-control technologies are being explored.

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Non-thermal plasmas (NTPs) are a type of advanced oxidation & reduction process which use free radicals to decompose pollutants in the gas phase.

<table>
<thead>
<tr>
<th>Non-thermal plasmas are a type of AOP making use of “cold combustion” via free-radical reactions. Electrons are energetic (<em>hot</em>), while neutral &amp; ions are at near-ambient temperatures (<em>cold</em>).</th>
<th>Applications</th>
</tr>
</thead>
</table>
| The key idea is to direct electrical energy into favorable chemistry for oxidizing and/or reducing pollutants to more manageable forms (simpler or mineralized terminal products). | • Flue gases & engine emissions: e.g., NO\textsubscript{x} & SO\textsubscript{x}  
• **VOCs**: e.g., hydrocarbons & halocarbons  
• **Odors**: H\textsubscript{2}S, others |
| | Potential Advantages |
| | • In-situ generation of chemical reactants  
• No added fuel (greenhouse gases)  
• Simultaneous removal of multiple pollutant species  
• Electronic feedback for optimal process control. |

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Non-thermal Plasmas Decompose Pollutants Via Active Species Generated in the Process Gas

Influent Stream (w/pollutants) → Electrical Energy → Plasma & active species (e.g., free radicals) → Effluent Stream (w/decomposed pollutants, simpler compounds)
The radical production efficiency (G-value) depends on the gaseous electronics/plasma chemistry.

\[ G = f \left( \frac{k_{rad}}{E} \right) \left( \frac{E}{V_d \frac{N}{}} \right) \]

- Radical generation is mainly initiated by energetic-electron collisions,
- \( E/N \) is the reduced field,
- \( V_d \) is the electron drift velocity, which depends on \( E/N \),
- \( k_{rad} \) is the rate constant for radical formation (e.g., a dissociation rate constant, which depends on \( E/N \)), and/or other rate constants.

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The overall process efficiency can be effectively separated into two terms: the radical production efficiency and the radical utilization efficiency.

\[ \eta_{\text{net}} = G_R \eta_u \]

- \( G_R \) is the radical-production efficiency (mainly depends on gaseous electronics/plasma chemistry)
- \( \eta_u \) is the radical utilization efficiency (mainly depends on chemical kinetics)
Gas-phase plasma chemical decomposition is driven by electron impact and radical attack.

(1) \( e + X \rightarrow \text{products} \)

(2) \( \text{O, OH, N, etc.} + X \rightarrow \text{products} \)

- The first reaction is dominant at large pollutant mole fractions.
- The second dominates at smaller mole fractions.

(More energy is directly absorbed by pollutant at high mole fraction, hence electron channel dominates.)

<table>
<thead>
<tr>
<th>Plasma chemical decomposition of VOCs produces a variety of terminal products.</th>
</tr>
</thead>
<tbody>
<tr>
<td>( e, \text{O, OH, N, etc.} + X \rightarrow \text{products} )</td>
</tr>
<tr>
<td>• Manageable products: ( \text{CO}_2, \text{CO}, \text{Cl}_2, \text{HCl, COCl}_2 )</td>
</tr>
<tr>
<td>• Undesirable products: Other halocarbons, hazardous byproducts (e.g., DCAC - ( \text{CHCl}_2\text{COCl} )); polymers</td>
</tr>
<tr>
<td>• Secondary treatment:</td>
</tr>
<tr>
<td>( \text{CO}_2 + \text{NaOH} \rightarrow \text{NaHCO}_3 )</td>
</tr>
<tr>
<td>( \text{CO} + \text{catalyst} \rightarrow \text{CO}_2 )</td>
</tr>
<tr>
<td>( \text{Cl}_2 + \text{NaHCO}_3 \rightarrow \text{NaCl} + \text{HCl} + \ldots )</td>
</tr>
<tr>
<td>( \text{HCl} + \text{NaOH} \rightarrow \text{NaCl} + \text{H}_2\text{O} )</td>
</tr>
<tr>
<td>( \text{COCl}_2 + \text{H}_2\text{O} \rightarrow 2\text{HCl} + \text{CO}_2 )</td>
</tr>
</tbody>
</table>

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Major de-NO\textsubscript{x} Reactions in Moist Gas Mixtures w/o HCs

\begin{align*}
O + NO + M &\rightarrow NO_2 + M \\
O + NO_2 &\rightarrow NO + O_2 \\
O + N_2 &\rightarrow NO + N \\
O + O_2 + M &\rightarrow O_3 + M \\
O_3 + NO &\rightarrow NO_2 + O_2 \\
O_3 + NO_2 &\rightarrow NO_3 + O_2 \\
NO_2 + NO_3 + M &\rightarrow N_2O_5 + M \\
N^{(2)D} + O_2 &\rightarrow NO + O \\
N + NO &\rightarrow N_2 + O \\
N^{(2)D} + NO &\rightarrow N_2 + O^{(1)D} \\
N + NO_2 &\rightarrow N_2O + O \\
N + NO_2 &\rightarrow 2NO \\
N^{(2)D} + H_2O &\rightarrow NH + OH \\
NH + NO &\rightarrow N_2 + OH \\
NH + O_2 &\rightarrow NO + OH \\
NO + NO_3 &\rightarrow 2NO_2 \\
NO + OH + M &\rightarrow HNO_2 + M \\
OH + HNO_2 &\rightarrow NO_2 + H_2O \\
OH + NO_2 + M &\rightarrow HNO_3 + M \\
N + NO_2 &\rightarrow N_2 + O_2 \\
N + N_2O &\rightarrow NO + N_2 \\
O^{(1)D} + NO_2 &\rightarrow NO + O_2 \\
O^{(1)D} + N_2O &\rightarrow 2NO \text{ or } N_2 + O_2 \\
N_2(A) + O_2 &\rightarrow N_2 + 2O \\
N_2(A) + N_2O &\rightarrow N_2 + N + NO
\end{align*}

Primary Acid-Formation Pathways:

\begin{align*}
NO + OH + M &\rightarrow HNO_2 + M \\
OH + NO_2 + M &\rightarrow HNO_3 + M
\end{align*}
The presence of SO$_2$ recycles OH radicals & reduces effective de-NO$_x$ energy cost

\[
\begin{align*}
\text{OH} + \text{SO}_2 + \text{M} & \rightarrow \text{HSO}_3 + \text{M} \\
\text{HSO}_3 + \text{O}_2 & \rightarrow \text{HO}_2 + \text{SO}_3 \\
\text{HO}_2 + \text{NO} & \rightarrow \text{NO}_2 + \text{OH}
\end{align*}
\]

The OH radical then goes on to be used again in de-NO$_x$

\[
\begin{align*}
\text{OH} + \text{NO} + \text{M} & \rightarrow \text{HNO}_2 + \text{M} \\
\text{OH} + \text{HNO}_2 & \rightarrow \text{NO}_2 + \text{H}_2\text{O} \\
\text{OH} + \text{NO}_2 + \text{M} & \rightarrow \text{HNO}_3 + \text{M}
\end{align*}
\]

Acid is also formed by the reaction

\[
\begin{align*}
\text{HSO}_3 + \text{H}_2\text{O} & \rightarrow \text{H}_2\text{SO}_4
\end{align*}
\]
With ammonia (NH₃) addition, useful particulates (fertilizer) can be formed from NOₓ

\[
e + \text{NH}_3 \rightarrow \text{NH}_2 + \text{H} + \text{e} \\
e + \text{NH}_2 \rightarrow \text{NH} + \text{H} + \text{e} \\
\text{NH} + \text{H} \rightarrow \text{N} + \text{H}_2 \\
\text{NH}_2 + \text{NO} \rightarrow \text{N}_2 + \text{H}_2\text{O} \\
\text{NH} + \text{NO} \rightarrow \text{N}_2 + \text{OH} \\
\text{N} + \text{NO} \rightarrow \text{N}_2 + \text{O}
\]

\[
\text{OH} + \text{NH}_3 \rightarrow \text{NH}_2 + \text{H}_2\text{O} \\
\text{OH} + \text{NO} + \text{M} \rightarrow \text{HNO}_2 + \text{M} \\
\text{OH} + \text{HNO}_2 \rightarrow \text{NO}_2 + \text{H}_2\text{O} \\
\text{OH} + \text{NO}_2 + \text{M} \rightarrow \text{HNO}_3 + \text{M} \\
\text{NH}_3 + \text{HNO}_3 \rightarrow \text{NH}_4\text{NO}_3 \text{ (Ammonium Nitrate fertilizer)}
\]
A generalized removal equation depends on plasma chemistry (radical yields), reaction chemistry, and applied plasma specific energy.

Generalized differential equation:

$$k[X] + \sum_i k_{S_i} [S_i] \frac{d[X]}{k[X]} = -G d\bar{E}$$

Integration with limits $[X]_0 \rightarrow [X]$ and $0 \rightarrow \bar{E}$ gives:

$$\frac{[X]}{[X]_0} + \frac{\sum_i k_{S_i} [S_i]}{k[X]_0} \ln \frac{[X]}{[X]_0} - 1 = -\frac{G\bar{E}}{[X]_0}$$

For low degree of removal (i.e., $[X]/[X]_0 \sim 1 + \ln \{[X]/[X]_0\}$), an analytical solution is obtained:

$$\frac{[X]}{[X]_0} = \exp\left(-\frac{\bar{E}}{\beta}\right)$$

where

$$\beta = \frac{1}{G} \left(\frac{[X]_0 + \sum_i k_{S_i} [S_i]}{k}\right)$$

When $k[X] \ll \sum_i k_{S_i} [S_i]$, the $\beta$-value and, hence the degree of removal $[X]/[X]_0$ shows no dependence on the initial concentration $[X]_0$.
Example scaling laws for pollutant removal
(non-sensitive $[X]_0$ dependence)

\[ [X] = [X]_0 \exp \left( -\frac{\bar{E}}{\beta} \right), \]

where $[X]_0$ is the initial pollutant concentration, $[X]$ is the resulting concentration, $\bar{E}$ is the applied specific energy (or plasma power divided by gas flow rate, $P/Q$), and $\beta$ is the e-fold energy density. Supplying one $\beta$ to the reactor reduces the concentration by $1/e$, $2\beta$ by $1/e^2$, and so on.

A useful figure of merit for the decomposition of pollutants is defined by the energy delivered to the plasma per hazardous molecule removed from the gas stream. At any instant, this can be expressed as the following quantity obtained by solving Equation 1 for $\bar{E}$ and taking the derivative:

\[ \gamma_i = -\frac{d\bar{E}}{d[X]} = -\frac{d[-\beta \ln(\frac{[X]}{[X]_0})]}{d[X]} = \frac{\beta}{[X]}. \]

This is the instantaneous energy cost per molecule removed.
Scaling laws for pollutant removal (cont’d)

A more practically-useful parameter is the integral, or average, energy cost $\gamma$

$$\bar{E} = \frac{\gamma}{[X]_0 - [X]} = \frac{-\beta \ln\left(\frac{[X]}{[X]_0}\right)}{[X]_0(1 - \frac{[X]}{[X]_0})} \quad (= \beta/[X]_0 \text{ (at optimum; i.e., } [X]/[X]_0 \sim 1).$$

Here, the energy cost per molecule is expressed in terms of the $\beta$-value, the degree of removal, and the initial concentration.

When radical-pollutant attack dominates $\beta \approx [X]_0/G$ and the removal cost is then independent of the initial concentration

$$\gamma = \frac{\bar{E}}{[X]_0 - [X]} = \frac{-\ln\left(\frac{[X]}{[X]_0}\right)}{G(1 - \frac{[X]}{[X]_0})} \quad (= 1/G \text{ at optimum; i.e., } [X]/[X]_0 \sim 1).$$

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Scaling laws for pollutant removal (graphical forms)

Energy costs and degree of removal for NO removal in an NO-air mixture with one e-fold plasma specific energies of 50 J/liter and 20 J/liter. NO is a compound whose β-value is not very sensitive to the initial concentration; therefore, the removal energy costs decrease as the concentration increases (note 200 ppm case vs 100 ppm case).
NTP pilot-unit setup for de-NOx field tests
## Expected exhaust-gas data and conditions

<table>
<thead>
<tr>
<th>Source Data</th>
<th>Variable</th>
<th>Units</th>
<th>JETC Values</th>
<th>CMTC Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas Flow</td>
<td>$Q_{gas}$</td>
<td>Nm$^3$/h</td>
<td>1.0E+05</td>
<td>6.6E+03</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1.7E+06</td>
<td>1.3E+04</td>
</tr>
<tr>
<td>Fuel</td>
<td></td>
<td></td>
<td>JP-8</td>
<td>JP-10</td>
</tr>
<tr>
<td>Final Exhaust-Gas Composition</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$N_2$</td>
<td>$C_{N2}$</td>
<td>%</td>
<td>80.98</td>
<td>78.00</td>
</tr>
<tr>
<td>$O_2$</td>
<td>$CO_2$</td>
<td>%</td>
<td>18.00</td>
<td>21.00</td>
</tr>
<tr>
<td>$CO_2$</td>
<td>$CCO_2$</td>
<td>%</td>
<td>0.50</td>
<td>0.50</td>
</tr>
<tr>
<td>$H_2O$</td>
<td>$CH_2O$</td>
<td>%</td>
<td>0.50</td>
<td>0.50</td>
</tr>
<tr>
<td>Density (Normal)</td>
<td>$D_{gas}$</td>
<td>kg/Nm$^3$</td>
<td>1.283</td>
<td>1.283</td>
</tr>
<tr>
<td>Exhaust Gas Temperature</td>
<td>$T_{gas}$</td>
<td>C</td>
<td>25</td>
<td>25-75</td>
</tr>
<tr>
<td>NTP Inlet Temperature</td>
<td>$TNT_{Pin}$</td>
<td>C</td>
<td>25</td>
<td>25-30</td>
</tr>
<tr>
<td>Pressure</td>
<td>$P_{gas}$</td>
<td>mm Hg</td>
<td>720</td>
<td>720</td>
</tr>
<tr>
<td>Emission Data</td>
<td>$NO_x$</td>
<td>ppm</td>
<td>36.00</td>
<td>&lt; 10</td>
</tr>
<tr>
<td></td>
<td>$SO_2$</td>
<td>ppm</td>
<td>4.59</td>
<td>~ 1</td>
</tr>
<tr>
<td></td>
<td>$HC$ (VOC)</td>
<td>ppm</td>
<td>60.00</td>
<td>20-25</td>
</tr>
<tr>
<td></td>
<td>$CO$</td>
<td>ppm</td>
<td>53.36</td>
<td>~ 5</td>
</tr>
<tr>
<td></td>
<td>Particles</td>
<td>mg/Nm$^3$</td>
<td>-</td>
<td>~/&gt; 1.0</td>
</tr>
</tbody>
</table>

**NH$_3$ Stoichiometric Ratio to NO and SO$_2$: 1.5 for both JETCs and CMTCs**
NTP de-NOx System Examples

**Stand-Alone System**

NO + VOCs + Air \(\rightarrow\) NTP Reactor \(\rightarrow\) NO\(_2\), HNO\(_3\), N\(_2\)

**NO \(\rightarrow\) NO\(_2\) Conversion + Scrubber System**

NO + VOCs + Air \(\rightarrow\) NTP Reactor \(\rightarrow\) HNO\(_3\) \(\rightarrow\) Wet Scrubber

Dilute HNO\(_3\) (w / Na\(_2\)S\(_2\)O\(_3\))
NaNO\(_3\) + H\(_2\)O (w / NaOH)
Ca(NO\(_3\))\(_2\) + H\(_2\)O (w / Ca(OH)\(_2\))

**Injection Systems**

NO + VOCs + Air \(\rightarrow\) NTP Reactor \(\rightarrow\) NH\(_4\)NO\(_3\) \(\rightarrow\) ESP

Injection Gas

Particulate NH\(_4\)NO\(_3\) (Fertilizer)

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Pulsed Corona System

Pulsed or DC corona

Wire Electrodes
Electrostatic Precipitator

Reactor
Channels

Stack
Fertilizer

Pulse Generator

Hydrocarbons

Influent Gas

\[ \text{NH}_3 \quad \text{(C}_x\text{H}_y) \]
Dielectric-Barrier (Silent Discharge) System

Illustration of mobile dielectric-barrier NTP reactor system employed for VOC decomposition tests at McClellan AFB. Each plasma reactor tank operated at up to 10 kW of plasma power.

CRADAs with the Electric Power Research Institute (EPRI) & High Mesa Technologies (HMT) were an essential part of the development & fielding of this equipment.
Schematic diagram of commercial Tecolytic™ modified dielectric-barrier NTP reactor system for de-NO$_x$/SO$_x$ (flue-gas treatment)
Electron-Beam System
Schematic diagram of CRS reactor. Ammonia (NH₃) or methane (CH₄) are added to generate radicals that drive reactions leading to the formation of particulates; these particulates are then captured by the electrostatic precipitator. Some of the captured products are useful for agricultural fertilizer (e.g., ammonium nitrate, NH₄NO₃).
Corona Radical Shower (CRS) Lab-Scale Prototype at McMaster University
We have provided economic analyses for three hybrid NTP systems compared to conventional de-NO$_x$ systems

<table>
<thead>
<tr>
<th>Conventional</th>
<th>NTP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Selective Catalytic Reduction (SCR) + Wet Scrubbers</td>
<td>Pulsed Corona</td>
</tr>
<tr>
<td>Selective Catalytic Reduction (SCR) + Electrostatic Precipitator (ESP)</td>
<td>Electron-Beam</td>
</tr>
<tr>
<td><img src="Diagram.png" alt="Diagram" /></td>
<td>Corona Radical Shower (CRS)</td>
</tr>
</tbody>
</table>
Example: NO\textsubscript{x} -removal power requirement depends on exhaust gas flow rate, characteristic specific energy, and desired degree of removal.

(Assume stand-alone NTP system.)

- Typical removal scaling: \[ [X]/[X]_0 = \exp \left( - \frac{E_s}{\beta} \right) \],

where \( E_s = P/Q \), plasma power divided by gas flow rate and \( \beta = \text{specific energy for one e-fold removal} \).

For NO, \( \beta \sim 10 \text{ J/lit (e-beam)}; \sim 50 \text{ J/lit (electrical discharge)} \).

- Power requirement for one e-fold removal: \( P = Q \cdot \beta \).

<table>
<thead>
<tr>
<th>Small Source:</th>
<th>Large Source:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q \sim 100 \text{ SCFM (2832 lit/min)}</td>
<td>Q \sim 1x10^6 \text{ SCFM (2.83x10^7 lit/min)}</td>
</tr>
<tr>
<td>P \sim 472 \text{ W (e-b), 2.4 kW (e-d)}</td>
<td>P \sim 4.7 \text{ MW (e-b), 24 MW (e-d)}</td>
</tr>
</tbody>
</table>

— Los Alamos —
## Benchmarking Basis/Examples for Economic Analyses

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Reactor Type: Facility: JETC Exhaust</th>
<th>Pulsed Corona</th>
<th>Corona Shower ‘JETC’ Exhaust</th>
<th>Electron Beam Auto Tunnel</th>
<th>Conventional Power Plant</th>
</tr>
</thead>
<tbody>
<tr>
<td>[NO]₀</td>
<td>ppm</td>
<td>36</td>
<td>40</td>
<td>10</td>
<td>300</td>
</tr>
<tr>
<td>NOₓ Removal</td>
<td>%</td>
<td>56</td>
<td>90</td>
<td>70</td>
<td>80</td>
</tr>
<tr>
<td>[SO₂]₀</td>
<td>ppm</td>
<td>4</td>
<td>4</td>
<td>1</td>
<td>3,050</td>
</tr>
<tr>
<td>SOₓ Removal</td>
<td>%</td>
<td>90</td>
<td>95</td>
<td>95</td>
<td>90</td>
</tr>
<tr>
<td>Energy Yield</td>
<td>g-NO/kW-h</td>
<td>20</td>
<td>17</td>
<td>19</td>
<td>-</td>
</tr>
<tr>
<td>Exp. Scale</td>
<td>Nm³/h</td>
<td>600</td>
<td>12</td>
<td>40,000</td>
<td>1.9 x 10⁶</td>
</tr>
</tbody>
</table>


---

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Cost comparisons for various de-NO$_x$ systems
(70% de-NOx, 108 h/wk operation)

Gas Flow Rate: $1.0 \times 10^8$ Nm$^3$/h ($5.89 \times 10^4$ SCFM)

<table>
<thead>
<tr>
<th>($)</th>
<th>Pulsed Corona</th>
<th>Corona Shower</th>
<th>Electron Beam</th>
<th>Wet Scrubber + SCR</th>
<th>ESP + SCR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capital Recovery</td>
<td>345</td>
<td>410</td>
<td>718</td>
<td>36</td>
<td>104</td>
</tr>
<tr>
<td>Labor &amp; Maintenance</td>
<td>218</td>
<td>246</td>
<td>377</td>
<td>273</td>
<td>273</td>
</tr>
<tr>
<td>Electric Power</td>
<td>99</td>
<td>116</td>
<td>77</td>
<td>123</td>
<td>83</td>
</tr>
<tr>
<td>Chemicals &amp; Utilities</td>
<td>6</td>
<td>6</td>
<td>6</td>
<td>1,291</td>
<td>1,192</td>
</tr>
<tr>
<td>Total Annual Cost</td>
<td>664</td>
<td>774</td>
<td>1,176</td>
<td>1,723</td>
<td>1,651</td>
</tr>
<tr>
<td>Fertilizer Recovery</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
Cost comparisons for various de-NO\textsubscript{x} systems (cont'd.)
(70\% de-NOx, 108 h/wk operation)

Gas Flow Rate: $1.70 \times 10^8$ Nm\textsuperscript{3}/h (1.0 x 10\textsuperscript{6} SCFM)

<table>
<thead>
<tr>
<th>(k$$)</th>
<th>Pulsed Corona</th>
<th>Corona Shower</th>
<th>Electron Beam</th>
<th>Wet Scrubber + SCR</th>
<th>ESP + SCR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capital Recovery</td>
<td>3,594</td>
<td>4,151</td>
<td>6,504</td>
<td>3,802</td>
<td>3,123</td>
</tr>
<tr>
<td>Labor &amp; Maintenance</td>
<td>1,823</td>
<td>2,060</td>
<td>3,061</td>
<td>4,641</td>
<td>4,641</td>
</tr>
<tr>
<td>Electric Power</td>
<td>1,674</td>
<td>1,970</td>
<td>1,318</td>
<td>2,082</td>
<td>1,403</td>
</tr>
<tr>
<td>Chemicals &amp; Utilities</td>
<td>110</td>
<td>110</td>
<td>110</td>
<td>21,935</td>
<td>20,247</td>
</tr>
<tr>
<td>Total Annual Cost</td>
<td>7,139</td>
<td>8,230</td>
<td>10,931</td>
<td>32,459</td>
<td>29,414</td>
</tr>
<tr>
<td>Fertilizer Recovery</td>
<td>62</td>
<td>62</td>
<td>62</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

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Other workers have evaluated two additional NTP de-NO\textsubscript{x} & de-SO\textsubscript{x}/NO\textsubscript{x} systems (Air Force contract) (Pulsed corona oxidizer + scrubber)

Haythornthwaite et al

Tecogen/Thermo Power (Modified dielectric barrier)

\[ \text{NO} \rightarrow \text{NO}_2 \text{ Conversion + Scrubber System} \]

\[ \text{NTP Reactor} \]

\[ \text{Wet Scrubber} \]

\[ \text{NO}_2 \rightarrow \text{HNO}_3 \]

\[ \text{HNO}_3 \]

\[ \text{NO} + \text{VOCs} + \text{Air} \]

\[ \text{Dilute HNO}_3 \]

\[ \text{NaNO}_3 + \text{H}_2\text{O} \]

\[ \text{Ca(NO}_3)_2 + \text{H}_2\text{O} \]

\[ \text{w/ NaOH} \]

\[ \text{w/ Ca(OH)}_2 \]
Cost data for
Haythornthwaite et al 1997
4 x 10^6 SCFM JETC using PCR
NO → NO₂ converter + wet scrubber
(~50% NOₓ removal)

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Capital Cost</td>
<td>$109,200,000</td>
<td></td>
</tr>
<tr>
<td>Capital Recovery</td>
<td>$14,196,000</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Run Time</td>
<td>10 hr/week</td>
<td>50 hr/week</td>
</tr>
<tr>
<td>O &amp; M Costs/Yr</td>
<td>$523,600</td>
<td>$2,618,000</td>
</tr>
<tr>
<td>Annual Cost</td>
<td>$14,719,600</td>
<td>$16,814,000</td>
</tr>
</tbody>
</table>

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Cost comparisons for commercial Tecolytic™ modified dielectric-barrier NTP reactor system for de-NO$_x$/SO$_x$ (flue-gas treatment) show favorable trends.
Future trends

Realizing the performance and economic shortcomings of stand-alone NTP reactors, the use of staged or hybrid systems to better match particular air-emissions control applications is being more widely explored.

- NTP + injectants
- NTP + catalysts
- NTP + adsorbents

NTP technology may become more common in areas where it has significant advantages over conventional technologies in terms of:

- Increased efficiency and/or economics
- Increased selectivity or throughput
- Better control of final products and/or process
- Unique process streams

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Summary

- A greater awareness of the effects of air pollutants ($\text{NO}_x/\text{SO}_x$, VOCs, particulates) on our environment and human health has led to more stringent regulations on air emissions.

- Non-thermal plasma technology is being explored as an emissions-control option in several areas (this talk has emphasized $\text{NO}_x$ control in jet engine test facilities).

- Hybrid systems (e.g., using injectants) show increased removal yields and favorable economic trends for large-scale de-$\text{NO}_x$ systems.

- Rigorous pilot-plant tests are required to provide further data and operating experience to more fully evaluate economic and performance projections.

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